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R.P. Anantatmula
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7. Abstract

In the period from April to October of 1988, a series of welding operations on the outside of the AZ tank farm ventilation line piping produced unexpected and repeated cracking of the austenitic stainless steel base metal and of a seam weld in the pipe. The pipe was wrapped in polyethylene bubble wrap and buried approximately 12 feet below grade. Except for the time period between 1980 - 1987, impressed current cathodic protection has been applied to the pipe since its installation in 1974.

The report describes the history of the cracking of the pipe, the probable cracking mechanisms, and the recommended future action for repair/replacement of the pipe.

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EVALUATION OF CRACKING IN THE 241-AZ TANK FARM VENTILATION LINE

RP ANANTATMULA
LD BLACKBURN

Contributions also made by
JR DIVINE
J JO
JP HAUPTMANN
WC CARLOS

Prepared for the U.S. DOE - Richland Operations
Office by WHC Waste Management Technology.

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EXECUTIVE SUMMARY

In the period from April to October of 1988, a series of welding operations on the outside of the AZ Tank Farm Ventilation Line piping produced unexpected and repeated cracking of the austenitic stainless steel base metal and of a seam weld in the pipe. The ventilation line is fabricated from type 304L stainless steel pipe of 24" diameter and 0.25" wall thickness. The pipe was wrapped in polyethylene bubble wrap and buried approximately 12 feet below grade. Except for the time period between 1980 and 1987, impressed current cathodic protection has been applied to the pipe since its installation in 1974. The pipe contains vapors coming from the Aging Waste Tanks and operates at a temperature of about 110° F. However, occasional temperature excursions of the vent line to a maximum temperature of 170° F are also anticipated.

The first ventilation crack appeared after welding a branch connection to the pipe for the installation of a sample port. Welding a patch over this crack resulted in the appearance of a second crack adjacent to the fillet weld of the patch. During welding of another patch to cover the second crack, extensive cracking developed along the pipe seam weld.

Analysis of the pieces of a sample removed from the vent header inside the welded branch connection confirmed that the pipe was 304L stainless steel and was not sensitized. Evaluation of delta ferrite concentration of the girth weld and seam weld of the excavated pipe indicated ferrite distributions that are normally expected for the 304L stainless steel welds.

Detailed non-destructive examination (NDE) of the excavated pipe revealed, in addition to the cracks near the sample port and the two patch welds, transverse cracks near the girth weld, and transverse and axial cracks near the seam weld. Only three of the cracks observed in the excavated pipe are through-wall cracks. The transverse cracks are consistent with tensile circumferential stresses at that location and these cracks near the girth weld must have formed during service since NDE after completing the girth weld should have revealed the base metal cracking associated with pipe installation.

Since the ductility of 304L stainless steel is very large and the plastic strains produced by welding operations can be accommodated by the large ductility, the cracking, in general, of the ventilation line can only be explained by a combination of residual stress and active chemical species from the environment.

Several cracking mechanisms have been proposed to explain the weld cracking and the general cracking observed near the girth weld and the seam weld. The cracking mechanisms that are considered to be noteworthy are chloride stress corrosion cracking and hydrogen embrittlement.

Finally, recommendations were made for future action on the vent line. Although a preliminary safety evaluation indicated that the leakage of vent gases via the three through-wall cracks would not result in a significant increase in the existing hazard to the environment, it is recommended that options for repair of the cracked section should be pursued to assure complete containment of vent gases. Under normal operating conditions leakage is not expected since the vent line operates at a slight negative pressure relative to the outside environment. The repair option is suggested until the installation of a totally new vent line system under project W-202. It is also recommended that cathodic protection be applied to the vent line continuously and that the operating voltage on the cathodic protection system be maintained between -1 and -2 V. Regardless of whether it is repair of the subject pipe section or total replacement of the vent line, it is recommended not to cover the new pipe section/pipe with the bubble wrap while providing continuous cathodic protection.

EVALUATION OF CRACKING IN THE 241-AZ TANK FARM VENTILATION LINE

1.0 INTRODUCTION

In the period from April to October of 1988, a series of welding operations on the outside of the 241-AZ ventilation line piping produced unexpected and repeated cracking of the austenitic stainless steel base metal and of a seam weld in the pipe. Three of the cracks at the seam weld extended through the pipe wall. The piping is part of the ventilation system for the four Aging Waste Facility tanks and had been buried for 14 years. The through-wall cracking represents an unacceptable condition for this system. This report presents an interim assessment of the possible causes for the cracking and reviews options for correcting the present defective condition of the ventilation line.

The ventilation line is made from 304L stainless steel pipe of 24-inch diameter and 0.25-inch wall thickness. The pipe was wrapped in polyethylene bubble wrap and buried approximately 12 feet below grade in 1974. Impressed current cathodic protection was applied to the pipe since installation in 1974 until 1980. The cathodic protection system was disconnected from 1980-1987. The application of cathodic protection, however, has been continuous since 1987. The pipe contains vapors coming from the Aging Waste Tanks and operates at a temperature of about 110° F. However, occasional temperature excursions of the ventline to a maximum temperature of 170^0 F are also anticipated. A portion of the pipe was excavated in 1988 to install a port for obtaining vapor samples from inside the line.

The first ventilation line crack appeared after welding a branch connection to the pipe for the sample port. Grinding to a depth of about 0.025 inch below the pipe surface did not eliminate the crack. Initial evaluation attributed the cracking to a lamination problem. A straight-beam ultrasonic test examination detected a lamination in the pipe wall below the crack. However, a second ultrasonic test found no lamination. After welding a patch over the original crack, a second crack appeared adjacent to the fillet weld of the patch. During welding of another patch to cover the second crack, extensive cracking developed along the pipe seam weld. The installation fillet welds exhibited no cracking. This situation led to a series of examinations and tests to learn more about the condition of the piping and the stainless steel itself. Sections 2.0 and 3.0 of this report present the results from these examinations and tests.

Section 4.0 of this report contains a discussion of the environmental conditions external to the piping. Sections 5.0 and 6.0 examine how environmentally-assisted cracking processes might explain some or all of the observed cracking behavior.

Finally, Section 7.0 presents ideas for development of acceptable actions to correct the condition of the vent line.

2.0 PIPING BEFORE SERVICE

The specification (Vitro, 1972) for the vent line required electric-fusion-welded pipe produced to the requirements of ASTM A358-70, Class 2, using ASTM A240-70, Grade TP 304L plate. The Class 2 designation means no radiographic examination was required. Weld joints were to be double-welded, full-penetration welds made in accordance with procedures and by operators qualified in accordance with the ASME Boiler and Pressure Vessel Code, Section IX. Pipe was to be heat treated at a minimum temperature of 1900° F (1038° C) and quenched in water or otherwise rapidly cooled, unless some other heat treatment (including the option of no final heat treatment) was specified on the order. The ASTM Standard Specifications also require:

- The plate and deposited weld metal to conform to chemical composition requirements,

- The plate to conform to tensile property requirements,
- The welded joint to conform to a tensile strength requirement in a transverse tension test,
- Each length of pipe to be subjected to a hydrostatic test to a pressure which would produce in the pipe wall a stress of 75 percent of the minimum specified yield strength of the plate.

Original purchase records for the pipe and material test reports supplied by the manufacturer that might have confirmed conformance to the above requirements are no longer available.

Pacific Northwest Laboratory (PNL) conducted a chemical analysis and tension test on pieces of a sample removed from the vent header inside the welded branch connection (Divine, 1989). Results of the analysis were as follows:

Element	Composition (Weight %)
C	0.018
Cr	18.1
Ni	9.36
Mn	1.63
Si	0.54
S	0.0016
N	0.109
Fe	balance

This information confirms that the pipe was 304L stainless steel.

The tension test specimen was cut so that the gage section contained the center 1/8 inch of the 1/4 inch wall. Results of the test were as follows:

Yield strength - 38.3 ksi
Tensile strength - 97.2 ksi
Total elongation - 82.2%

Both yield strength and tensile strength of the test sample are slightly higher than the corresponding properties selected by Smith (1969) to evaluate properties of 304L stainless steels. Sikka et al., (1976) showed that the yield and tensile strengths of twenty heats of 304 stainless steel plate and pipe supplied to ASTM specifications were generally reduced after a laboratory solution heat treatment. These authors attributed the higher strength (observed in the present case) to a small amount of residual cold work (e.g., 3-4%) introduced in final processing operations (e.g., bending or straightening) that followed the manufacturer's heat treatment. A later section of this report will review evidence suggesting that the pipe was solution heat treated after the plate was formed and welded. Strength properties of the vent header sample, therefore, likely reflect the presence of some residual cold work.

Delta ferrite content of pipe seam welds (made by the pipe manufacturer) as well as a field girth weld (made when the vent header was installed on site by J.A. Jones work forces) were measured. The measuring instrument simply determined whether the delta ferrite content was less than or greater than discrete values of 2.5, 5.0, 7.5 or 10.0%. Appendix A contains details of measurement locations and delta ferrite levels. Basically, the delta ferrite level in seam welds of two separate pipe sections was less than 2.5%. The delta ferrite content of the girth weld was between 7.5% and 10.0%. Measurements on the base metal portion of the pipe indicated a delta ferrite level less than 2.5%, which is consistent with the expected value of zero for the 304L stainless steel.

The chemical composition, tensile properties and delta ferrite contents actually apply to material subjected to many years of service in the vent line, rather than on as-fabricated or as-installed material. However, there is a good reason to expect that the measurements are indeed representative of the starting material. At the low operating temperature, chemical contamination of the bulk material which could alter composition or changes in metallurgical structure which could alter mechanical properties or delta ferrite levels are virtually impossible[1].

The ductility of 304L or 304 stainless steel (these grades are considered equivalent in terms of ductility) is very large. The ductility data on the twenty heats of 304 stainless steel from Sikka et al., (1976) are the following:

TEMPERATURE	UNIFORM ELONGATION, %	TOTAL ELONGATION, %	REDUCTION OF AREA, %
Room Temperature	>60	>65	---
1200 °F	>25	>36	>45

These failure ductilities are far larger than the plastic strains which can be developed in welding operations. Since the material strain capacity is not exceeded, welding should not produce cracking in the 304 stainless steel base metal. Even allowing for a significantly lower failure ductility under multi-axial loading and deformation, cracking would not be expected. This reasoning is, of course, totally consistent with the almost universally successful experience in welding 304 stainless steel without base metal cracking.

The fracture toughness of 304 stainless steel base metal and of 308 stainless steel weld metal is also very high (Mills, 1984). Propagation of some pre-existing crack by the action of welding-induced thermal deformation is extremely unlikely. Mills (1984) points out that components must contain large cracks (e.g., tens of centimeters in length) and be stressed well into the plastic region before ductile tearing increases crack size. Extensive plastic deformation is required to create a tearing instability (i.e., unstable crack extension). Welding operations simply do not produce the extensive deformation required to significantly extend pre-existing cracks.

[1]Bulk contamination by hydrogen is possible, and this issue will be addressed later in the report.

The above considerations lead to the conclusion that since cracking of the ventilation line (i.e., normal 304L stainless steel) cannot be explained by deformations of the magnitude expected around welds, some sort of environmental effect at the surface or internal contamination of the material must have occurred during service to cause the cracking. Later sections of this report will explore this idea in greater detail.

3.0 PIPING IN SERVICE

This study evaluated the ventilation line by laboratory examinations and tests on a sample removed from the pipe (Divine, 1989) and by field examination of excavated piping. The preceding section presented information judged applicable to material prior to service. The following two subsections give additional information on material subjected to service exposure.

3.1 LABORATORY EXAMINATIONS AND TESTS

Analysis of the sample removed from the ventilation line showed a hydrogen concentration of 9 ppm by weight. Two other samples of Tank Farm piping removed a number of years ago both analyzed 1 ppm hydrogen. However, we have not established that the apparently higher hydrogen concentration in the ventilation line sample is atypical of 304L stainless steel. If hydrogen were distributed non-uniformly, surface concentrations could be significantly higher than the analysis value, which represents an average over the wall thickness. More recently, hydrogen analysis of a second sample from the ventilation line indicated a concentration of 8 ppm by weight. The sample was obtained from the top 1/8 inch layer of the piece extracted from the ventilation line. However, the sample was not analyzed until two years after the piece was originally cut out from the ventilation line, which may have resulted in diffusion of some of the hydrogen out of the sample.

Installation and/or moving of the lead blankets for radiation shielding could leave isolated lead contamination on the pipe surface. Initial chemical analysis of the ventilation line sample revealed a lead content of 0.72 percent by weight. A repeat sampling and analysis failed to detect any lead.

Electrochemical potentiokinetic reactivation (EPR) is a measurement to determine the degree of intergranular carbide precipitation (termed sensitization) in austenitic stainless steels. Measured EPR values indicated the ventilation line sample was not sensitized.

The PNL study used scanning electron microscopy to view the sample surface, and electron dispersive x-ray spectroscopy to define the sample surface chemistry. The outside surface of the sample showed signs of abrasion and had numerous particles in the gouges. The particles typically contained Ca, K, Al and some Ti. Analyses of the soil by x-ray fluorescence analysis showed the presence of these same elements. This indicates that the pipe surface might have been in contact with the soil in this region either before or during service. Metallographic analysis of a cross-section through the pipe wall revealed no significant surface attack or damage.

3.2 FIELD EXAMINATIONS

Examination of the excavated ventilation line progressed in several stages. Figure 1 is a map showing all the areas examined by visual and liquid penetrant methods. In the eight areas examined (identified as Regions B through I, in Figure 1) only Regions D and E exhibited a consistent pattern of cracking. Figure 2 presents a schematic illustration of the observations in these two areas.

Liquid penetrant examination around the fillet weld attaching the branch connection to the ventilation line revealed the first evidence of cracking. A single crack about 2-1/4 inches long appeared in the base metal about 1/2 inch away from the weld. Cracking caused by a very high temperature failure process should occur very close to the weld, where the temperatures are highest and thermally-induced plastic strains are greatest. The observed

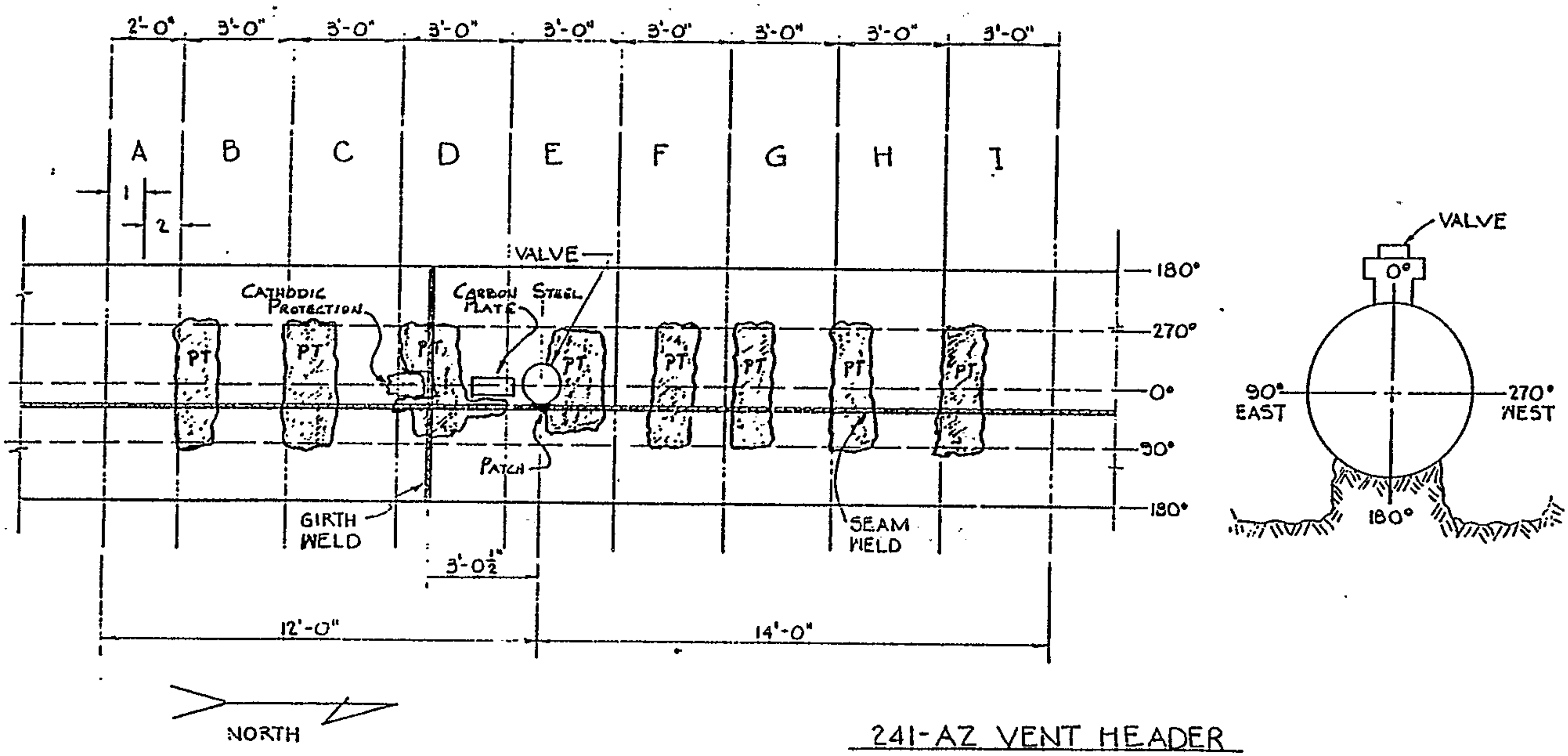

Figure 1: Regions of AZ Tank Farm Ventline Examined by Visual and Liquid Penetrant Methods.

9 2 1 2 5 6 2 1 2 9 3

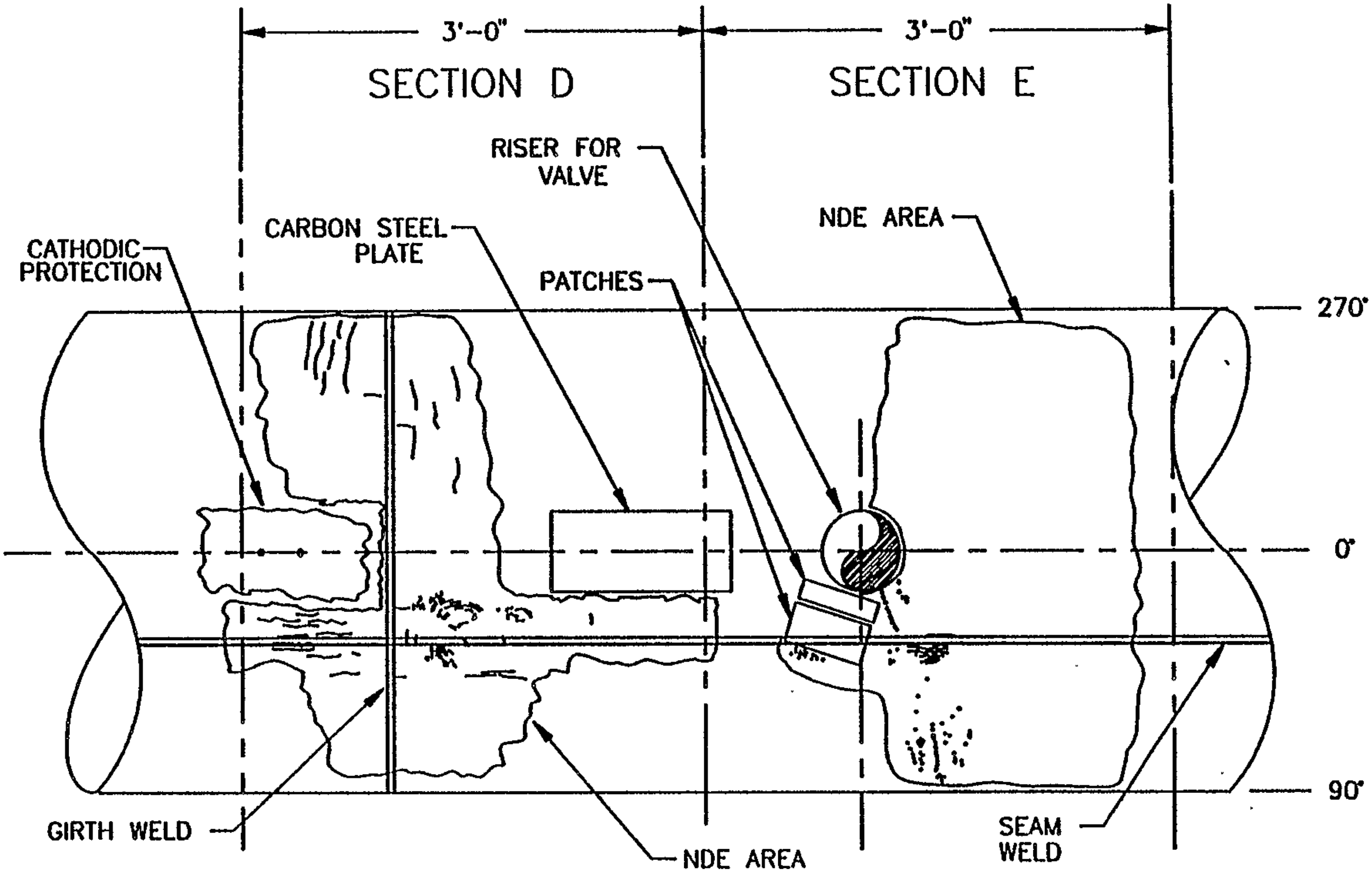

Figure 2: Schematic Illustration of Observations in Regions D and E.

crack location suggests an intermediate temperature or low temperature failure process driven by residual stresses generated on cooling. The distribution of residual stress around a circular patch weld given by Masubuchi (1980, Page 203) should be qualitatively similar to that around the branch connection. A moderately high radial stress (the maximum value attainable is the material yield stress at ambient temperature) could occur outside the weld itself. Such a stress is basically consistent with the observed crack location.

A second crack about 1-1/4 inches long developed about 1/2 inch away from and parallel to a fillet weld made during installation of a rectangular patch to cover and seal the first crack. A qualitative model for the residual stress distribution around the fillet weld is that given by Masubuchi (1980, Page 193) for a restrained weld in a flat plate. That model suggests the stress transverse to the weld extends well into the base metal and could account for the orientation and location of the second crack.

Installation of another rectangular patch to cover and seal the second crack caused more cracks. Although residual stress around the fillet weld for the second patch should be similar to that for the first patch, the cracking response was markedly different. Cracks appeared in or near the pipe seam weld oriented transverse to the seam weld, rather than parallel to the patch fillet weld. Visual observations revealed two cracks located in the seam weld about 1/4 inch away from each corner of the patch prior to completing welding on the second patch. Although centered in the seam weld, these cracks extended into the base metal. These cracks were presumed to be through-wall cracks for the following reasons:

- Liquid penetrant could not be contained in the cracks

- Liquid (from moisture inside the ventilation line) was observed in the cracks

- Radioactive contamination was detected on smears from the cracks.

The final visual examination of Region E revealed a third crack across the seam weld about 2 inches from the north corner of the second patch. Liquid penetrant examination failed to detect this crack also, so it was classified as a through-wall crack.

A small area of intense cracking occurred in the base metal several inches north of the second patch just below the seam weld. The crack orientation was generally axial, but with some circumferential character evident.

The circumferential girth weld is a convenient location to start the cracking in Region D of the ventilation line. Four axial (i.e., transverse to weld direction) cracks occurred in base metal adjacent to the weld; no other cracking occurred within about one inch on either side of this weld. Residual stresses surely exist in and around this field weld, since post-weld heat treatment would not have been applied. The residual stress distribution given by Masubuchi (1980, Page 207) should represent the qualitative features of the girth weld stresses. Transverse cracks near the weld are consistent with tensile circumferential stresses at that location. Compressive axial stress on the outside surface is consistent with an absence of circumferential cracks. Liquid penetrant examination conducted after completing the girth weld should have revealed base metal cracking associated with pipe installation, so transverse cracks near the girth weld must have formed during service. This finding suggests that the other cracking in this region also developed during ventilation line service.

Residual stress in the weld metal itself is at least as high as that in the adjacent base metal, yet no weld metal cracking occurred. The weld metal is, therefore, more resistant to the cracking mechanism than is the base metal.

Cracking in the pipe south of the girth weld occurs at two different locations. Axial cracks appear in the base metal on both sides of the seam weld at distances of 1-8 inches from the girth weld. At least one circumferential crack along the seam weld fusion line changes to transverse orientation proceeding into the weld (or vice versa). However, pronounced transverse cracking of the seam weld did not occur.

On the west side of the south pipe, well away from the seam weld, there is a pattern of circumferential cracking. At the extreme edge of the examined region, the crack pattern appears to be changing toward an axial orientation.

In the pipe north of the girth weld, eight transverse cracks occur in the seam weld at distances of 1-8 inches from the girth weld, but no seam weld cracks occur at distances of 8-24 inches from the girth weld. One small area of intense cracking occurs in the base metal just below the seam weld about 5 inches from the girth weld; the orientation of this cracking is basically circumferential (i.e., the same as transverse cracks in seam weld), but some small axial cracks also seem to be present. About 2-3 inches above the seam weld, there is a base metal cracking pattern which extends from 2-12 inches north of the girth weld. Near the girth weld, the cracks are oriented circumferentially, but they gradually change toward an axial orientation farther from the girth weld. A similar, but less well-developed, type of cracking is observed several inches below the seam weld. On the west side of this pipe a number of faint, isolated cracks with circumferential orientation are evident.

4.0 SERVICE ENVIRONMENT

4.1 SOIL

Although differences exist between different regions in density, granulation and drainage, soils at the Hanford site are alkaline (average pH=8.2), well drained and are of extremely low mineral content (Jaske, 1955). Because of their sandy nature, the Hanford soils can be considered to be highly aerated. The average resistivity of the Hanford soil is 5000 ohm-cm, which falls slightly above the average resistivity of the soils tested by the National Institute of Standards and Technology (previously known as National Bureau of Standards). Soil sample analyses at Hanford indicated an average of 0.01 mg equivalent of chloride for 100 g of sample, which translates to over 2 ppm of chloride in the water contained in the soil. Therefore, very little general corrosion by soils is expected of the construction materials (steels) buried at Hanford. However, differences in electrochemical potential along the exposed steel surface do occur due to differences in mineral content or oxygen concentration of soils, and differences in chemical makeup of neighboring regions of the steel surface, resulting in localized galvanic attack. Such attack is normally slowed down or stopped by polarization of the steel.

For stainless steel buried in Hanford soils, a corrosion mechanism of a more serious nature was observed to be pitting underneath the coatings by incrustations of calcareous nature due to establishment of oxygen deficiency cells. Thus, cathodic protection was recommended in the 1940s to be applied to buried stainless steel waste lines at Hanford to eliminate the pitting corrosion. The same principle has also been applied to the AZ Tank Farm ventlines. In addition to the application of cathodic protection, the AZ Tank Farm ventlines were also covered with bubble wrap at the time of installation in 1974. This was done to provide a cushion and minimize the stresses during unanticipated thermal cycling of the pipe as well as to eliminate the physical contact of the pipe with the soil.

4.2 BUBBLE WRAP

The bubble wrap used for covering the AZ Tank Farm vent pipe is made of polyethylene and is not expected to contain any chloride. Although it is not indestructible, bubble wrap uncovered after approximately three years of underground service in the tank farms appeared to be in good condition. However, the bubble wrap on the AZ ventline has been in service since 1974 and as such it may or may not be an effective barrier between the pipe and the soil in certain locations, permitting the passage of sand and/or moisture.

Bubble wrap recently unearthed from the AZ ventline was charred in appearance in some areas of the pipe. At the present time, the reason for charring is unknown. The charring could not have been caused by radiation or by the assumed temperature of the vent pipe. The radiation levels were not high enough to cause this phenomenon. In addition, the maximum operating temperature of the waste tanks in the AZ Tank Farm is 260^0 F. Moreover, when the bubble wrap (polyethylene) is heated in the presence of air it is expected to dissociate into carbon dioxide and water. The charring might have been a result of charred paper wrap or adhesive on the bubble wrap. In any event, the charring of the bubble wrap appears to be in locations remote from the cracked regions of the pipe.

4.3 CATHODIC PROTECTION

Cathodic protection can be defined as reduction or elimination of corrosion by making the metal a cathode by means of an impressed direct current or attachment to a sacrificial anode. Cathodic protection was first applied to the AZ ventline system at installation in 1974. However, the cathodic protection system was disconnected during 1980-1987. With the bubble wrap as an insulating barrier between the pipe and soil, the protection current requirements are less than those for a bare pipe. The voltage required for complete cathodic protection of a bare austenitic stainless steel tank has been determined to be -0.75 V with reference to a saturated calomel electrode (SCE) by Castillo and Arnold (1981). However, during the 1974-1980 time period, voltages as high as -10 V (with reference to SCE) were reportedly used with bubble wrap in place. The cathodic protection system of the AZ vent pipe has been in continuous operation again since 1987 with an impressed voltage of -2 V.

5.0 CRACKING MECHANISMS

Some active chemical species from the environment or from contamination on the pipe surface must have played a key role in producing the observed cracking. The following discussions examine three mechanisms - stress corrosion cracking, hydrogen embrittlement, and liquid metal embrittlement - that offer an explanation for the cracking.

5.1 STRESS CORROSION CRACKING

Stress corrosion cracking (SCC) is defined as cracking of a metal under an applied tensile stress in a corrosive environment. Stress corrosion cracking propagation occurs by an electrochemical process. Simply stated, the passive film on the material is ruptured by the combined action of active chemical species such as chloride and tensile stress resulting in crack initiation. The area where the film is ruptured becomes the anode and the large cathode area is the metal covered with the passive film. In other words, the crack tip essentially becomes the anode and dissolution at the tip continues until eventually the material fails. Since SCC is electrochemical in nature, at least in part, in both its initiation and propagation, an electrolyte has to be present. Cracking has been reported even under conditions where moisture can be present only as a very thin, usually unrecognized, film.

It is quite possible that water vapor might have been trapped in the annulus between the bubble wrap and the pipe at the time of installation of the bubble wrap on the pipe. It is quite likely that the water vapor, thus trapped, would have condensed on the pipe during service. It is assumed here that the bubble wrap is fairly intact in most regions of the pipe. In the regions where the bubble wrap is not a protective barrier, water from the soil may also have condensed on the pipe. As stated earlier, the bubble wrap does not contain any chlorides but the water from the soil is expected to contain at least 2 ppm of chloride.

Stress corrosion cracking by chlorides usually occurs above about 140° F (Peckner and Bernstein, 1977). The risk of SCC increases as either chloride or temperature or both increase. Scharfstein and Brindley (1958) reported that Types 304 and 347 stainless steels cracked in the temperature range of 165 to 200° F in dilute chlorides (20 to 100 ppm) at a pH of 7. Williams and Eckel (1956) were able to produce cracks in an 18-8 stainless steel in water containing 1 ppm of chloride at 500° F, providing oxygen was present. Logan et al., (1963) produced cracking in austenitic stainless steel in a solution containing 5 ppm chloride at 575° F with oxygen present. The above results indicate that SCC of Type 304 stainless steel can occur in water containing low concentrations of chloride ($\geq$ 1 ppm) and at as low a temperature as 165° F with oxygen present. It should be noted, however, that the work described here was carried out in a laboratory where the results were obtained in a few hours. Based on the above discussion, it is quite probable that the SCC of the vent pipe could have been initiated during the high temperature excursion (170° F) of the ventline under the combined action of the low chloride solution, oxygen and residual stresses.

Although the subject pipe was buried approximately 12' underground, because of the good drainage of the Hanford soil, the water contacting the pipe is expected to contain enough oxygen for crack initiation to occur. In fact, recent literature surveys (Farmer et al., 1988) indicated that SCC of Type 316L stainless steel can be initiated in solutions containing low chloride ($\leq$ 0.1 ppm) and low oxygen ($\leq$ 0.1 ppm) concentrations. In addition, the survey points out that Type 304L stainless steel is more susceptible to SCC than Type 316L stainless steel.

The above-mentioned crack initiation by chlorides and possible propagation could have occurred, even during 1974-1980 when cathodic protection was present, due to the chlorides in the moisture trapped under the intact bubble wrap. This is because the cathodic protection current will be essentially zero on the pipe surface under the intact bubble wrap. However, in regions where moisture entry was made possible by the deterioration of the bubble wrap, such SCC initiation and propagation could have occurred only during 1980-1987 when cathodic protection was not applied to the vent pipe. This is because cathodic protection, when properly applied, has been widely accepted to prevent SCC or stop its slow propagation (Logan, 1966).

Stress corrosion cracking by caustic usually occurs at concentrations of about 20% and at high temperatures (about 260° F). Hydroxide can form in the vicinity of bare pipes that are buried and cathodically protected. As discussed earlier, the bubble wrap on the ventilation line should make cathodic protection ineffective over much of the pipe surface, so extensive hydroxide formation is unlikely. Since neither a high concentration of hydroxide nor a sufficiently high temperature exist at the ventilation line, caustic SCC is not a likely mechanism for the cracking.

From the above discussion, it follows that chloride seems to be the most likely active species for SCC in the ventilation line. The x-ray fluorescence analysis of the soil discussed in Section 3.0 could not detect chloride at low levels where SCC might still occur. Other analysis methods have not yet been applied to soil samples from the ventilation line excavation.

5.2 HYDROGEN EMBRITTLEMENT

Cathodic protection, if not properly applied, can lead to hydrogen embrittlement in steels. Hydrogen embrittlement of austenitic stainless steels is not normally cosidered a problem. Overprotection of structures by employing greater than the required level of impressed currents, to a moderate degree, usually does not cause any problems. The primary disadvantages are wastage of electric power and increased consumption of auxiliary anodes. When overprotection is excessive, hydrogen can be generated at the protected structure in sufficient quantities to cause hydrogen embrittlement of steel or hydrogen cracking. In the case of Type 304 stainless steel, this could lead to surface cracking in the absence of applied loads and residual stress as suggested in the literature (Holzworth, 1969, and Wasielewski and Louthan, 1985). However, if the bubble wrap is effective in limiting cathodic protection to small areas, then a more widespread hydrogen embrittlement mechanism is less likely.

Radiolysis of moisture around the pipe by the radiation field is an alternative source of active hydrogen specie, but the radiation intensity (dose rate 200 mR/hr) at the ventilation line seems too low for this mechanism to produce a significant quantity of hydrogen.

Generation of excessive amounts of hydrogen at the stainless steel pipe surface could lead to the diffusion of atomic hydrogen into the pipe material and raise the local hydrogen concentration to a level that substantially reduces the ductility in that region of the material. Since the solubility and diffusivity of hydrogen in Type 304 stainless steel are low, the atomic hydrogen is only expected to penetrate to shallow depths from the surface at a fairly low bulk hydrogen concentration. Under these conditions, fairly steep concentration gradients can be achieved, resulting in expansion of the lattice in regions just below the surface. This would lead to development of tensile stresses during the hydrogen outgassing period resulting in the appearance of surface cracks in these regions (Wasielewski and Louthan, 1985). In this case, the cracking process might proceed along the following sequence of steps.

1. Surface deformation and compressive plastic flow due to the expansion of the lattice during the hydrogen entry

2. As hydrogen outgasses from the pipe, tensile stresses begin to develop

3. The combination of high tensile stresses and high hydrogen content in the lattice near the surface causes surface cracking.

In the present case, such cracking near the stainless steel pipe surface could have occurred (even in the absence of external [residual] stresses) during the period from 1980-1987 when the cathodic protection system was turned off. This might have been the reason for the appearance of some of the surface cracks during the non-destructive examination of the pipe away from the cracks produced in the heat affected zone by patch welding.

There is also another type of hydrogen embrittlement in which the combination of composition, temperature and fugacity are such that hydrogen is absorbed in the lattice without accompanying surface cracking (Burke et al, 1975). The extent of embrittlement is determined by the hydrogen concentration and can also be as large as the type discussed above that produces the surface cracking. In this case, cracking can result due to the combined action of hydrogen embrittlement and suspected high residual stresses.

The occurrence of surface cracking does not, in any way, compromise the integrity of the bulk austenitic stainless steel material. The mechanical properties of the bulk material are not expected to undergo significant changes by this surface phenomenon.

The increase in the surface concentration creates a driving force for diffusion of hydrogen into the remainder of the steel. The maximum depth to which hydrogen can diffuse and raise the local concentration can be approximated by the following relation:

$$X = 2\ (Dt)^{0.5}$$

where,

X = depth of hydrogen penetration

D = diffusivity of hydrogen in austenitic stainless steel

t = time allowed for hydrogen diffusion

The review of hydrogen diffusivity in austenitic stainless steels by Caskey (1981) yields nominal and upper bound D values at 140° F (60° C) of 1×10^{-11}

cm^2/sec and $1x10^{-10}$ cm^2/sec, respectively. Assuming diffusion time of 6 years (time the cathodic protection system was operational), predictions of hydrogen penetration are as follows:

Diffusivity, cm^2/sec	Penetration (inch)	
	6 years	14 years
$1x10^{-10}$	0.108	0.165
$1x10^{-11}$	0.034	0.052

These calculations indicate that hydrogen should not have penetrated the pipe wall, and may in fact be confined to the outer 20% of the wall.

A hydrogen embrittlement mechanism appears to be consistent with the cracking in Region D of the ventilation line. Residual stress should be an important driving force for cracking. The clear preference for axial or circumferential crack orientation in most of the section does not seem consistent with stresses generated by hydrogen charging. Depth of cracking should not exceed the depth of hydrogen penetration, so through-wall cracking should not occur in this section. Extended service under conditions similar to those of the past could, however, lead to complete penetration of the wall by hydrogen, and through-wall cracking would be possible when residual stress extends through-wall.

5.3 LIQUID METAL EMBRITTLEMENT

Liquid metal embrittlement (LME) is considered a possible cracking mechanism primarily because lead appeared in the chemical analysis of a pipe sample. Lead blankets used for radiation shielding offered a ready explanation for the presence of lead contamination on the pipe surface. Failure by LME is frequently intergranular. Liquid metal embrittlement requires a critical strain and degradation is not progressive. Failure is equally likely after a long or short exposure. Fracture generally occurs by fast crack propagation. Although metals other than lead (e.g., Zn and Cu) can produce LME in austenitic stainless steels, we have no evidence of potential contamination by other embrittlers. In addition, the higher melting points of other embrittlers further reduces the likelihood they influence cracking, as later discussion will show.

6.0 INTERPRETATION

The applied loading on the ventilation line is estimated to be very low, so residual stress is the likely driving force for any cracking mechanism. Circumferential residual stress should exist around the girth weld, as discussed earlier. The reason more extensive cracking did not occur around the girth weld may be that the residual stress is relatively low. The propensity for cracking in the seam weld just north of the girth weld and around the second patch indicates this weld is very susceptible to the cracking mechanism. The absence of extensive cracking all along the seam weld suggests that residual stresses from welding do not exist along the seam; the pipe in all likelihood was heat treated after the seam weld was made. The residual stresses responsible for the cracking pattern away from the girth weld likely originated from nonuniform plastic deformation in final fabrication, handling, or installation operations. The clear preference for axial or circumferential crack orientation in most of Region D does not seem consistent with stress generation from hydrogen charging in the pipe surface. The more complex pattern might be consistent with hydrogen-induced stress generation, but could also be explained by residual stress in an area of complex deformation.

The cracking in Region D gives no indication that the active specie is distributed in a nonuniform pattern. For example, the observed pattern does not suggest concentration of an active specie near a seam or gap in the plastic wrap. Either stress corrosion cracking or hydrogen embrittlement could be responsible for the cracking. Liquid lead embrittlement would not explain the cracking. Temperature is too low for lead melting, and lead smears from the shielding would likely be nonuniformly distributed.

Both SCC and pitting corrosion have been known to be suppressed in cathodically protected stainless steel structures. However, chloride SCC could have occurred in the present case even during the application of cathodic protection. This is because the cathodic protection current will be essentially zero on the pipe surface under the intact bubble wrap. Stress corrosion cracking initiation and propagation could have also occurred, during the time the cathodic protection system was turned off, in regions where moisture entry was made possible by the deterioration of the bubble wrap. Visual examination of the ventilation line revealed general light pitting throughout the excavated area. Therefore, a SCC mechanism for cracking is still possible given the manner in which cathodic protection was applied.

Both SCC and hydrogen embrittlement can produce time-dependent cracking, so continued slow growth of existing cracks is possible. Residual stress at the girth weld should extend through the wall, so continued crack growth depends on a supply of active specie. Growth behavior of the other cracks in Region D will depend on the extent of the residual stress field, which is unknown, as well as on the availability of active specie. Prediction of future crack growth is not possible given the lack of quantitative information now available.

Interpretation of cracking around the welds in Region E involves some additional considerations. Residual stress around the branch connection and first patch should be higher near the weld than at the actual crack location. This fact suggests more extensive cracking should be observed near the weld. For a SCC mechanism, the active specie may be volatile at the high temperature portion of the thermal cycle, and thus is no longer available when stresses are generated on cooling. However, relatively rapid crack propagation must have occurred. Rapid crack extension is difficult to explain by a SCC mechanism, since there is no liquid environment to support rapid transfer of the active specie to the crack tip. On the other hand, a lead LME mechanism should exhibit more extensive cracking at the very high temperatures. The liquid phase and thermally-induced strains offer a greater potential for rapid grain boundary penetration at high temperature. A hydrogen embrittlement mechanism should be markedly affected by the weld thermal cycle. The initial high hydrogen concentration near the pipe surface should be reduced as hydrogen diffuses out of the surface to the environment and also further into the pipe wall. Extensive hydrogen redistribution could lead to the absence of cracking near the weld because the hydrogen content fell below the value required to produce cracking. Farther away from the weld, the redistribution is less extensive and cracking might occur. In view of the cracking patterns in Region E, the cracking in the base metal away from the welds might be expected from hydrogen redistribution.

Both SCC and hydrogen embrittlement mechanisms might lead to continued growth of the existing cracks or initiation of new cracks in future service. Residual tensile stress should exist through the pipe wall, so crack growth would be limited by transport of active specie to the crack tip. We have no evidence that the base metal cracks extend through the pipe wall. Redistribution of hydrogen within the pipe wall was apparently not extensive enough to lead to through-wall cracks. Continued slow growth could occur, however, either by hydrogen diffusion through adjacent areas of pipe or by hydrogen supply down the crack via the environment.

The same considerations discussed above apply to the cracks at the seam weld in Region E, but now the propensity for through-wall cracking must be explained. On the pipe surface, the transverse seam weld cracks extend well into the base metal, but the crack profile through the wall thickness is unknown. At this time, it appears that through-wall cracks result from some unique condition existing in or around the seam weld.

9 2 1 2 5 5 2 1 3 0 7

7.0 RECOMMENDED FUTURE ACTION

In principle, limited surface cracking on the pipe could be accepted. Structural integrity of pipe with existing flaws can be demonstrated by methods of fracture mechanics. In addition, calculations should show that future slow growth would be acceptable. However, at the present time, knowledge of the cracking process is insufficient to conduct such evaluations. Even if the mechanism were known, information on fracture toughness values and kinetics of crack growth needed for a quantitative assessment is not available.

Although the vent line is under a slight negative pressure relative to the outside environment, a preliminary safety evaluation has been completed (Fein, 1991) to determine the acceptability of the through-wall cracks, as they represent a path for release of radioactive contamination. The safety evaluation results indicate that, under normal operating conditions, leakage of vent gases via the three through-wall cracks would not result in a significant increase in the existing hazard to the environment. In spite of this assessment, options for repair of the cracked section should be pursued to assure complete containment of any leakage of the vent gases through the through-wall cracks. Such repair of the cracked section is recommended to assure compliance of the ventline with current regulations until a totally new ventline system is installed under project W-202 in 1997.

One of the repair options could be to repair the ventline by encasing the section containing the three through-wall cracks and the surface cracks in a larger diameter pipe. The larger diameter pipe could be fitted over the ventline section like a clam shell and seam-welded. The annulus between the two pipe sections at both ends could then be mechanically sealed. Other options such as cutting and replacing the affected section by welding or mechanical means should also be evaluated and the most appropriate method for repair selected. If the present ventline needs to be attached to the ventline proposed under project W-030, prior to the installation of the new ventline system of project W-202, a successful method for welding to the ventilation line would have to be demonstrated. Earlier considerations of possible cracking mechanisms suggest that successful welding could be achieved if the pipe surface was thoroughly cleaned (to remove active species) and a bake-out operation (to remove hydrogen) was developed. Verification of successful weld operations could be achieved by performing welding tests which include test pieces that are constrained to simulate the actual service conditions of the vent line.

In closing, regardless of the responsible mechanism for cracking of the pipe and whether it is repair of the subject pipe section or total replacement of the vent line, it is recommended that cathodic protection be applied to the vent line continuously and that the operating voltage on the cathodic protection system be maintained between -1 and -2 V and not exceed -2 V. In order to eliminate the possibility of cracking of the repaired section or the new ventline system due to the combined action of residual stresses and wet chloride environments, it is recommended that the pipe section/pipe be not covered with the bubble wrap while providing continuous cathodic protection.

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APPENDIX A

Westinghouse
Hanford Company

Internal Memo

From: Materials Applications
Phone: 3-1817 S2-03
Date: November 7, 1990
Subject: FERRITE CONTENT OF 241-AZ VENT HEADER WELDS

To: R. P. Anantatmula R2-12

cc:	L. M. Bergman	R1-51
	L. D. Blackburn	H5-53
	W. C. Carlos	H5-52
	J. Jo	R2-11
	G. D. Johnson	L5-03
	N. W. Kirch	R2-11
	W. F. Zuroff	R2-12

The results of the ferrite measurements conducted November 7, 1990 on the 241-AZ vent header are as follows:

1. The vent header seam welds have a ferrite content of less than 2.5% as measured with a Severn Engineering Co. indicator.

2. The upper patch weld has a ferrite content of greater than 5.0% but less than 7.5%.

3. The lower patch weld has a ferrite content of greater than 7.5% but less than 10.0%.

4. The girth weld has a ferrite content of greater than 7.5% but less than 10.0%.

5. The vent header base metal has a ferrite content of less than 2.5%.

The attached Inspection Record identifies the measurement locations.

J. P. Hauptmann

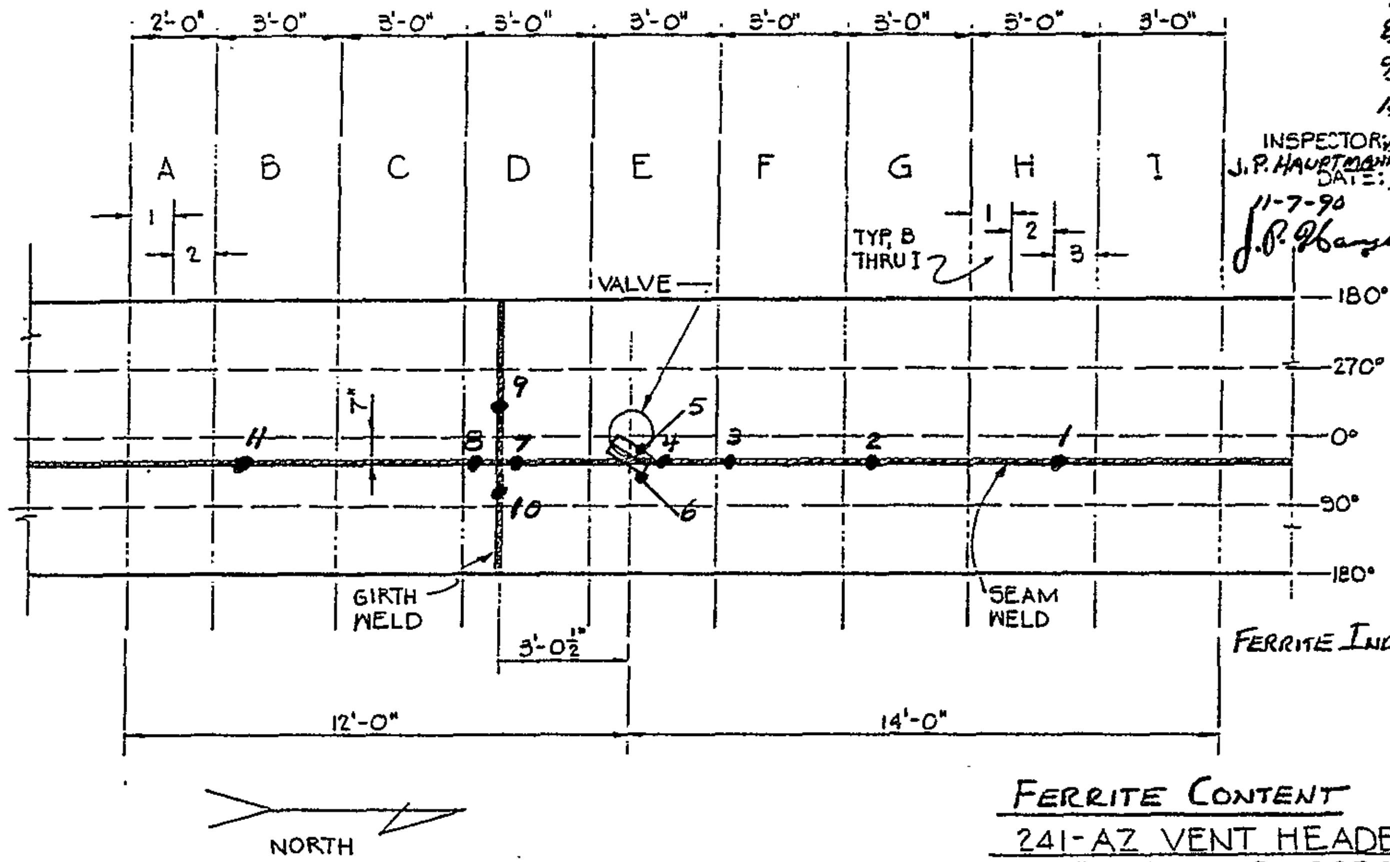
J. P. Hauptmann
Welding Engineer

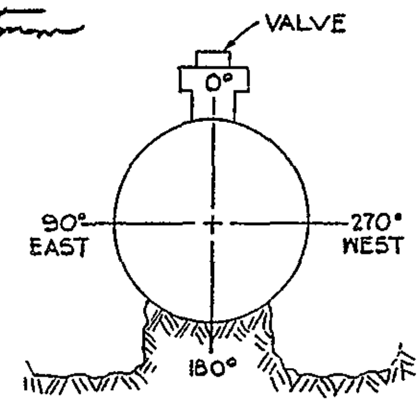
sgs

Attachment

NOTE: 1) 10' NORTH OF VALVE : < 2.5
2) 6' NORTH OF VALVE : < 2.5
3) 3' NORTH OF VALVE : < 2.5
4) SEAM WELD AT PATCH : < 2.5
5) UPPER PATCH WELD : > 5.0, < 7.5
6) LOWER PATCH WELD : > 7.5, < 10.0
7) NORTH SEAM AT GIRTH WELD : < 2.5
8) SOUTH SEAM AT GIRTH WELD : < 2.5
9) GIRTH WELD AT 315° : > 7.5, < 10.0
10) GIRTH WELD AT 45° : > 7.5, < 10.5
11) 8' SOUTH OF VALVE : < 2.5
RANDOM BASE METAL : < 2.5

INSPECTOR: J.P. HAUPTMANN
DATE: 11-7-90





FERRITE INDICATOR: SEVERN ENGINEER Co.
5049
KEH INVENTORY # 328

FERRITE CONTENT
241-AZ VENT HEADER
INSPECTION RECORD

PAGE 1 OF 1

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